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BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D.C. 20024

SUBJECT: The 3°K Radiation Field
Case 630

DATE: January 16, 1969

FROM: W. A. Gale

ABSTRACT

We review the considerable experimental evidence for a 3°K black body radiation background in space. The cosmological hypotheses which suggested the search are discussed. We examine the signal and accuracy requirements, and instruments capable of fulfilling them. Since atmospheric radiation limits the experiments, we consider various platforms used for mounting observations. We find that none of them has been fully exploited yet, and that reasonable doubt of the interpretation is likely to remain until some satellite-based measurements have been made.

(NASA-CR-103978) THE 3 DEG K RADIATION FIELD (Bellcomm, Inc.) 11 p

N79-72370

Unclas
00/18 11505

FF No. 602(A)

(PAGES) (CODE)

CR #103978

(NASA CR OR TMX OR AD NUMBER) (CATEGORY)

[redacted]

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MEMORANDUM FOR FILE

INTRODUCTION

The background radiation from space at 7 centimeters wavelength was recently measured by Penzias and Wilson.[1] The results excited considerable interest among astrophysicists and cosmologists. Dicke et al.[2] had expected to find such a radiation field from predictions of the big bang cosmologies, and put forth a cosmological explanation at that time. The background radiation at centimeter wavelengths is commonly described as that expected from a black body at 2.7°K, but the detailed shape of the spectrum including the wavelength for maximum energy has not yet been determined. Alternative descriptions are given below with the data. This is followed by the cosmological hypotheses which predicted such radiation. We then discuss the requirements for measurement of the spectrum and anisotropy, the equipment available at the wavelengths of interest, and the possible vehicles in which to mount the experiments.

DATA

The spectrum of the background radiation has been measured at several wavelengths from 21 cm to 3 mm, and its anisotropy with spatial direction has been measured at 3.2 cm. The spectral measurements are summarized in Table I. Some of the measurements are made from the ground, some from mountain tops. The following descriptions can each be supported by the data:

(1) The spectrum is that of a black body with $T = 2.68 \pm .12°K$

(2) The temperature dependence on wavelength is not that of a black body, but rather $T \propto \lambda^n$, $n = .00 \pm .06$

(3) The spectrum is that of a grey body with emissivity $1 \geq e \geq .7$, $eT = 2.68 \pm .12°K$

The temperature of either a black or grey body must be independent of wavelength, hence (2) is compatible with (1) or (3) only if n=0. A grey body is black only if the emissivity is one. The bulk of these measurements were made with a Dicke radiometer switched between the sky and a liquid helium load. The anisotropy of the field, measured by the difference of signal in two opposite directions as percent of average signal, has been found to be .03 ± .07% at 3.2 cm.[3] This experiment consisted of measurements of the radiation field toward the celestial equator, for fifty-five day long runs, over a period of a year.

COSMOLOGICAL HYPOTHESES[4,5]

Cosmologies are models of the gross features of the universe in time and space. A strong assumption widely used is that the basic laws of physics (especially conservation of energy, and second law of thermodynamics) hold universally in time and space. Most cosmologies further assume isotropy and homogeneity of all fields (matter, radiation, neutrino, ...) in the universe. These isotropic models are characterized by the sign of curvature $k(+1,0,-1)$ and by an expansion function $R(t)$, which has dimensions of length given as a function of time. A cosmology with $R(0) = 0$ is called a Big Bang cosmology, since at small times, the whole universe is compressed into very small distances, from which it expands quite rapidly.

For small t, and hence small $R(t)$, energy conservation implies a high density of energy, i.e. high temperature (10^{10} °K). Detailed calculations of concentrations of various substances as a function of time have been made. These calculations assume constancy of dynamical equations (Schrodinger's equation) and such structural parameters of the universe as the speed of light and nuclear interaction cross sections. For $t<1$ sec., i.e. at the time of the big bang, these calculations give a picture of a universe in which neutrinos have a short mean free path, gamma radiation freely produces relativistic electrons, where there are no complex nuclei, and protons and neutrons are about equal in number. Since characteristic times for these processes are 10^{-23} sec, the various fields are in thermodynamic equilibrium. In particular the radiation field is that of a black body, since this is by definition that field which results from thermodynamic equilibrium of matter and radiation at a given temperature. As the universe expands, both matter and radiation cool adiabatically. So long as the matter remains ionized, the radiation and matter fields interact through the electrons, remaining coupled and in equilibrium. When the plasma is cool enough for the protons and electrons to combine, forming neutral hydrogen which no longer interacts with the radiation, the residual radiation has an independent existence, cooling as the universe expands. The spectrum of the radiation field is not changed from that of a black body at any point in this process.

In so far as the description of the radiation field as that of a black body continues to hold, this hypothetical construction will be supported. Deviations from the black body curve would give valuable information on the last scattering of the radiation and on any reionization of matter.[6] Another theory[7] proposed intergalactic ionized hydrogen as the agent responsible for emission, but predicted $T \propto \lambda^{(4/5)}$, which can be rejected on the basis of the experimental results.

SPECTRAL MEASUREMENT

In the absence of an alternate theory to suggest critical wavelengths for measurement, the interpretation of the spectrum as that of a black body needs to be strengthened. The wavelength for maximum power in the spectrum has not yet been measured, and until it is, there will be uncertainty about the blackness or emissivity of the responsible agent. The radiation maximum for a black body occurs at 5.11/T mm, or 1.9 mm for 2.7°K. Hence measurements at 2 mm and shorter are needed, since wavelengths longer than 2 mm are now reasonably well covered.

Apart from the uncertainty of the position of the maximum, the interpretation of the measurements cannot be made with confidence until background measurements are extended to wavelengths in the decade shorter than 1 mm. When the principal emitters in the latter region are known, their theoretical contribution near 2 mm can be subtracted from the measurements.

The expected signal near 2 mm is about $6 \times 10^{-6} \times B$ erg/sec, where B is the bandwidth in percent. To improve present data, measurements are needed with an accuracy of better than 10%. The bandwidth does not need to be smaller than the desired accuracy since the bandwidth is the uncertainty in frequency. Several 10% measurements would be preferable to one 1% measurement.

ANISOTROPY MEASUREMENT

Anisotropy is spatial non-uniformity of a signal, and is measured by the difference of signal in two directions as a percent of the average signal. Intrinsic anisotropy is defined as the anisotropy visible to an observer at rest with respect to the source. Velocity anisotropy is the anisotropy resulting from motion of the observer, as his telescope scoops up more photons when approaching the source than when pointed away from it.

The anisotropy measurement is the best evidence for the cosmologists' isotropy assumption. When the data gathered from looking outward around the celestial equator over 50 days were analyzed in terms of hourly intervals (15°), no one direction was found to have amplitude more than 1/2% greater than average.[3] This implies that matter inhomogeneities on this 15° scale are less than 10%.[8] Before the measurement of intrinsic anisotropy can be pushed to lower limits, the velocity anisotropy will have to be measured in magnitude and direction.

It has been shown[9,10] that the net result of motion in an isotropic field of radiation at temperature T, is that the observer finds the temperature he measures, T', at the angle θ' from the direction of his motion is

$$T'(\theta') = T(1 - v^2/c^2)^{1/2} [1 - v/c \cos \theta']^{-1} \tag{1}$$

$$\cong T (1 + v/c \cos \theta'), \tag{2}$$

where v is the magnitude of the observer's velocity, and c is the speed of light. The relative velocity v is expected to be about 300 km/sec = 10^{-3} c since this is the orbital velocity of the solar system in the galaxy. (The velocity of the earth around the sun is about 10^{-4} c and may also be measurable soon.) Hence the expected signal difference between two directions is expected to be about 10^{-3} of the average signal at the same wavelength. A very large bandwidth is desirable for anisotropy experiments in order to increase the signal level. An infinite bandwidth radiometer taking the difference of the absolute signals from the two opposite directions along a line making an angle θ' with the direction of motion at 300 km/sec through space would register a signal difference of $8 \times 10^{-6} \times \cos \theta'$ erg/(sec cm^2 sr)[11] if it were subject only to an isotropic 3°K radiation field when at rest.

After anisotropy measurements have been fitted by Equation (1) with the best value of v, residual differences can be ascribed to intrinsic anisotropy. The velocity and amount of intrinsic anisotropy will both be extremely interesting.

EQUIPMENT

The millimeter region is being approached by extending microwave techniques to shorter wavelengths, and by extending infrared techniques to longer wavelengths. The cross-over is marked by difficulty of comparison of equipment working on different principles. In Table II, the sensitivity, or minimum detectable temperature change, ΔT, is set out for the major possibilities. It should be noted that the dependence of the sensitivity on bandwidth, B, is $\Delta T \propto B^{-1/2}$ for coherent (superheterodyne and maser) detectors, but $\Delta T \propto B^{-1}$ for incoherent detectors. The coherent radiometers have smaller bandwidths (1/10%) than the incoherent detectors (10%). The hypothetical performance to be expected if a broad band parametric amplifier were available for use with the coherent detectors is also shown.

The germanium bolometer at liquid He temperature, seems to have the best performance for the bandwidth and frequency desired. With an appropriate set of filters, several measurements could be made. However, the InAs photoconductor has already been adapted to rocket flight by Harwit, and the superheterodyne radiometer would not require liquid helium cooling.

Condon and Harwit(11) plan to use the InAs photoconductive radiometer in a broad-band anisotropy experiment from a rocket. A signal to noise ratio of 1 can be obtained for ΔV = 45 km/sec with 240 sec of integration time. The broad bandwidth allows reduction of experiment time from 55 days to 240 seconds. The adaptation of the germanium bolometer to space flight should improve this another order of magnitude. The present sensitivity will be an order of magnitude improvement over the Partridge and Wilkinson(3) experiment.

The anisotropy experiment is technically easier than the absolute power measurement, because a reference temperature source is not required. Variation in signal with direction is all that must be measured. The additional equipment for the absolute power measurement is usually a set of fiberglass spikes immersed in liquid helium to provide the reference temperature. Development would be required to adapt this to space conditions.

VEHICLES

We consider ground, balloon, airplane, rocket, and satellite. The factors pertinent to these experiments are atmosphere above vehicle, time of integration possible, manned experimentation, and structural requirements on the radiometer.

For wavelengths longer than 1 mm, water vapor is responsible for most of the atmospheric absorption, and hence unwanted emission which limits these measurements. Minima in the absorption curve occur at 1.3 mm, 2.2 mm, and 3.3 mm. These windows have about the same amount of absorption (1. db at sea level), so that it would seem possible to do experiments on a mountain top at 2.2 mm and 1.3 mm of accuracy comparable (50%) to the existing experiment at 3.3 mm. By the use of an airplane or balloon which can climb above 8 to 10 km, one has left only 1% of the water vapor to look through.(12) This would reduce a one way attenuation of 10 db to .1 db, which would render most of the region from 1 to 4 mm accessible to experiments.(13)

As we have pointed out, access to the wavelengths shorter than 1 mm will ultimately be required for clearcut interpretation of the longer wavelength results. In the region between 1 mm and .02 mm (1000 μ and 20 μ) water vapor is strongly attenuating. The attenuation is not reduced to .1 db until a height of 30 km is reached.(14) For this region, it is necessary to avoid the entire atmosphere, which can be done from rocket or satellite. Preliminary experiments can be done from rockets, but definitive studies will require satellites.

Noise is effectively diminished by the square root of the integration time (in seconds). The time possible on various vehicles is about 10^7 sec on ground, 3×10^4 sec in balloon, 7×10^3 sec(?) in airplane, 2×10^2 sec for rocket, 4×10^5 sec(?) for satellite.

Recalibration of the radiometer after use is important. Hence the radiometer should be recoverable, or the instrument should be manned in order to recalibrate. Harwit(15) is able to recover the InAs radiometer from rocket flight in working condition. Further work would be necessary on the germanium bolometer or a maser system.

SUMMARY

Both absolute and anisotropy measurements of the background radiation remain to be made in the region of wavelengths shorter than 2 mm. Ground based experimentation has not yet been fully exploited, since 50% measurements at 2.2 and 1.3 mm should be possible. No experience is available from balloon or airplane flights to indicate the limits of investigation attainable from these vehicles. Rocket based anisotropy experiments can be improved beyond those presently planned. These means seem likely to provide a 10% knowledge of background radiation to wavelengths as short as 1 mm.

To obtain a 10% knowledge below 1 mm, it seems that times greater than a few minutes above the atmosphere will be required; hence a satellite will be the necessary vehicle.

Recalibration of the radiometer is experimentally important, and requires either that the radiometer be recoverable, or that a man be present to recalibrate.

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Attachments
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Table I - II

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TABLE I

DATE	REFERENCE	WAVELENGTH	$\frac{T}{°K}$
1965	Penzias & Wilson[1]	7.0 cm	3.3 ± .5
1966	Penzias & Wilson[15]	21.0 cm	3.2 ± 1.0
1966	Howell & Shakeshaft[16]	20.7 cm	2.8 ± .6
1966	Thaddeus & Clavser[17]	2.63 mm	3.75 ± .5
1966	Field & Hitchcock[18]	2.63 mm	3.05 ± .35
1967	Welch et al.[19]	1.50 cm	2.0 + .8
1967	Stokes, Partridge, Wilkinson[20]	3.2 cm	2.69 ± .19
1967	Stokes, Partridge, Wilkinson[20]	1.58 cm	2.78 ± .14
1967	Wilkinson[20]	8.56 mm	2.56 ± .20
1967	Ewing, Burke, Staelin[21]	9.24 mm	3.16 ± .26
1968	Boynton, Stokes, Wilkinson[22]	3.3 mm	2.46 ± .42

TABLE II

REFERENCE	TYPE	WAVE-LENGTH	Hz BANDWIDTH	°K ΔT	°K OPERATING TEMPERATURE	ADAPTED TO	DATE
Barrett[23]	Superhet	5 mm	10^8 [10^{10}	.5 .05]	240	Satellite Hypothetical	1968 ——
Meredith[24]	Superhet	2 mm	10^8	6×10^4	300	Lab	1965
Bauer[25]	Point Contact	1 mm	10^6 [10^{10}	40 .4]	300	Lab Hypothetical	1966 ——
Arams[26]	Maser	8 mm	30×10^6	.2	3	Field	1965
Low[27]	Bolometer	Any	10^{10}	.06	3	Field	1966
Putley[28]	Photoconductive	5-8 mm	10^{10}	10	3	Rocket	1965
Putley[28]	Ideal Photo-conductive	5-8 mm	10^{10}	.1	3	Hypothetical	——

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